Varve Chronology

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1. Introduction

Chronology indicates a sequence of time and refers back to *Chronos*, the Greek God of time. The word "varve" needs an explanation, however (*varv* is a Swedish word denoting a full circle). It refers to a rhythmic sequence representing the deposition of sediments or growth of a precipitate over a time of 1 single year (as defined by De Geer, 1884, Högbom, 1889 and Johnston, 1922). Consequently, a varve is a sedimentological equivalent to the biological growth rings in a tree known as tree-rings.

Like tree-rings, the varves are measured as to thickness. The variations in thick-ness over a varve sequence are then used to establish correlations with another, nearby sequences (Fig. 1). By extending these sequences piece by piece over time, we establish a varve chronology.

This method was invented in the late 19th century by Gerard De Geer in Sweden (Fig. 1; further described in De Geer, 1940; Mörner, 1978; Francus et al., 2013). Therefore, it was often termed "the Swedish Varve Chronology" or "the Swedish Time Scale". Today, this chronology spans about 14,000 years from the present back in time. The method has been successfully applied in Finland, and also applied in many other areas of the globe (e.g. North America, the Alps, and Argentina).

Some sedimentary basins contain varved sediments where the individual varves may be counted separately (or at least approximated) so that site-specific long-term chronologies are established.

The present paper will be devoted to the Swedish Time Scale and the application of varve chronologies in general for precise dating of events, and calculations of rates.

Figure 1. Gerard De Geer demonstrating the varve chronological method in Essex Junction, US, in 1920 (where he made the first measurements already in 1891).

2. Building up the Swedish varve chronology

In 1884, the Swedish geologist Gerard De Geer observed in a channel excavation in Stockholm that the basal clay was laminated in a fashion, which made him think in terms of the annual growth rings in trees. He noted that the lamina consisted of a lower unit that was lighter in colour and courser in grain size and an upper clay unit that was quite dark. He named those couplets "varves" and claimed that they represented annual deposition (De Geer, 1884, 1940). In 1889, Högbom showed that the ratio of magnesium carbonate and calcium carbonate differed in the two units, and he interpreted this in terms the annual geochemical changes in the Baltic.

In 1904, a period of intensive construction of new houses stated in Stockholm. This gave rise to excellent exposures of the sediment beds, including the basal "varved clay" (as it was now called). De Geer measured new exposures, and to his surprise he noted that the new diagrams correlated well not only in between themselves, but also with the diagram he had measured 20 years before, located some 3 km to the east. This convinced him partly that the varves really were true annual varves, and partly that he would now be able to build up a continual chronology.

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With intensive work by De Geer himself and his students, a chronology was built up from Stockholm to central Sweden. By this he could demonstrate that it took 1073 years for the land-ice to retreat from Stockholm to Jämtland in central Sweden, a distance of 500 km. Already at the 1910 International Geological Meeting in Norden, he was able to give a detailed picture of the mode of ice recession after the last glaciation maximum around 20,000 years ago (De Geer, 1912).

2.1. Identifying and measuring varves

Because De Geer's primary aim was to date the recession of land-ice over Sweden, his and his students' work was concentrated on the oldest varve deposited in front of the receding ice margin. During the time of deglaciation, the crust was isostatically depressed by the load of the ice, causing relative sea level to be significantly higher than today. From the subglacial drainage system glacifluvial material was deposited in the form of eskers and varved clay with one varve for each year (as illustrated in Fig. 2).

The first varves to be deposited in front of the receding ice margin are strongly influenced by the glacial melting giving rise to varves composed of a coarse-grained summer unit (sandy-silty, sometimes even gravelly) and a fine-grained winter unit (clay to fine silt). In an esker environment, the first summer unit may include many meters of gravelly sediments (e.g. Bergström, 1968). De Geer (1940) interpreted the sand units of the proximal varves as being "flocculated" through the water column in front of the ice. Kuenen (1951) showed, however, that these units must have been deposited as turbidites (bed-load transport). The thick sandy summer units of proximal varves often exhibit rhythmic laminations. Ringberg (1984) counted some 50 laminae and proposed that they represented the number of summer days with open water conditions in the Baltic.

The clayey winter units represent the slow setting of suspended matter during the winters. These beds are often dark to black, exhibiting a reducing environment. During the winters, the lake and sea levels froze over, turbulence ceased and calm water conditions were established allowing suspended matter to settle.

The annual rhythmicity behind De Geer's glacial varves was the annual changes between melting in the summers and freezing in the winters. When the ice was gone some 9000 years ago, climatic conditions like to day were established. Even then, however, "postglacial" varved sedimentary sequences were formed in some lakes (Renberg, 1983) and especially in the deposits of the main rivers in the north due to the annual rhythm of a strong spring melting and low water discharge in late summers and winters (Lidén, 1913, 1938).

Besides the strict building up of "the Swedish Time Scale" via multiple short-distance varve correlations from Stockholm to north central Sweden, De Geer (1940) also attempted so-called "telecorrelations" over inter-continental and even inter-hemispheral distances. It seems to be an unfortunate mistake, however (not further discussed in this paper).

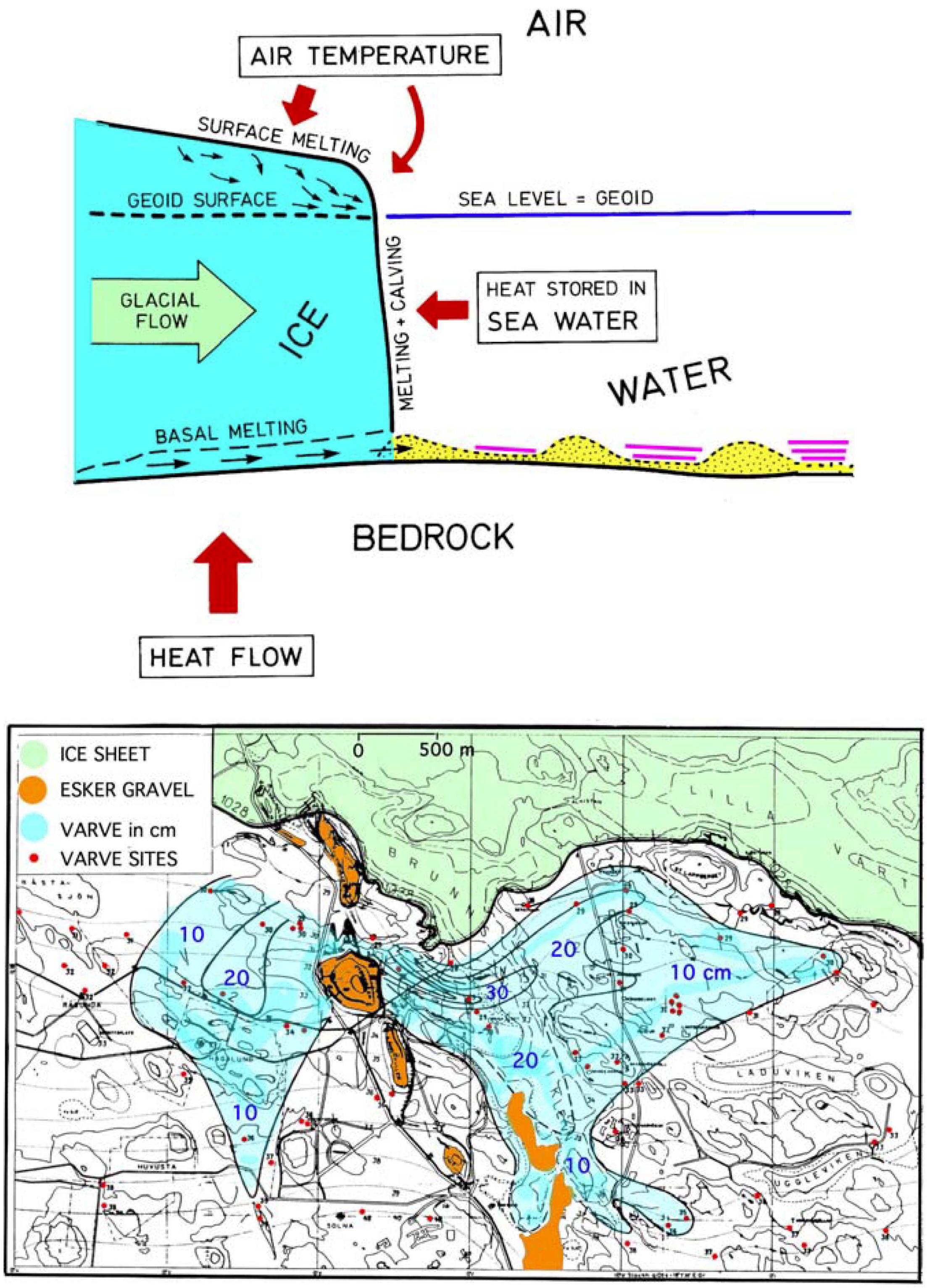

Figure 2. *Above:* The mode of ice melting, subglacial drainage and esker formation with 3 esker centra (yellow) and 3 successive annual varves (pink). *Below:* De Geer's (1940) map of the ice marginal position in year 10,385 BP, variations in thickness of this year's varve (blue), esker accumulations (orange) and varve sites (red dots). From Mörner (2008).

2.1.1. From field observations to chronological tools

The varves are observed and recorded in open pits or in cores. An open pit is always better because it allow us to view the lateral variations. In cores, very long and continual sequences can be obtained, however. The "Swedish Foil Piston Corer" was designed just for this purpose allowing the retrieval of undisturbed cores of 11 m length (e.g. Järnefors, 1963).

De Geer introduced the simple method of rolling out a paper stripe over the section or core of varves and marking each individual varve on the stripe. Then the individual varve thicknesses were measured and plotted on a diagram. The saw-tooth patterns of the varve diagrams were then used for inter-site correlations.

Varves of special characteristics, "marker-varves", were sometimes used for correlations (e.g. De Geer, 1940; Bergström, 1968; Strömberg, 1989). Mörner (e.g. 2013) did the opposite, used the varve chronology to prove that a "marker varve" represented one single event and had a very wide lateral distribution.

Fig. 3 shows two cores taken close to each other in two successive years. Even visually, it is easy to see the nearly identical variations in varve thickness. The varve diagram shows variations that allow the correlation with the main Swedish Time Scale, so that absolute ages are obtained. In this case, traces of two separate earthquakes were identified and dated (Mörner, 2003, 2013a).

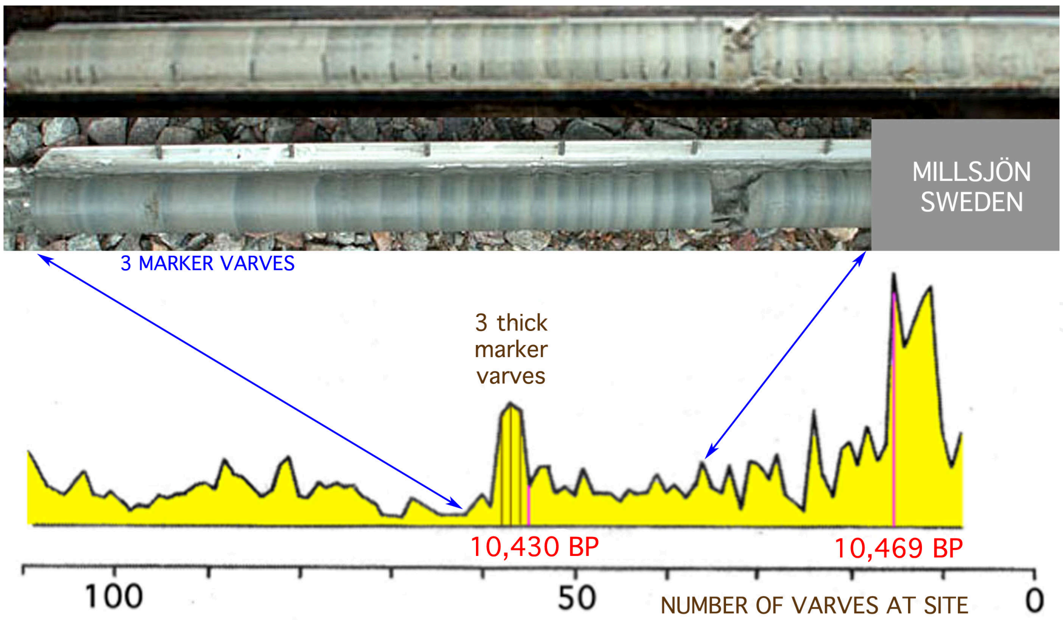

Figure 3. Varved clay cores take two years apart at approximately the same site. The inter-core correlations are very clear. The entire section includes 110 varves. Via the marker varves, the section can be correlated to the Swedish Time Scale and dated in absolute varve ages BP.

2.2. Additional applications

Lidén (1938) measured 7522 postglacial varves in the fluvial deposits occurring along the River Ångermanälven (plus a gap of 980 years to year 1900). By this, the varve chronology was fixed to the present and we were able to talk in terms of absolute years. De Geer's (1940) varve-1073 referring to the onset of the marine *Yoldia Sea* stage in the Baltic was now dated in absolute years at 9625 BP (later to be revised to 10,430 varves BP as discussed below).

Fromm (1938) measured pollen and diatoms in the same varves, implying that we from that time on were able to know the absolute ages of the immigration of different tree species, and the changes between fresh-water and marine stages of the Baltic.

Because Lidén's work referred to the succession of river deltas, he achieved a curve of the relative land uplift dated in absolute years BP (Fig. 4). It became a fundamental tool for the understanding of the concept of glacial isostsy (Gutenberg, 1941; Mörner, 1979).

All this was, of course, quite remarkable at a time period were we generally lacked other means of establishing absolute time.

The varve chronology flourished also in Finland (Sauramo, 1923), and was also applied to eastern North America by Antevs (e.g. 1932) and Patagonia (Caldenius, 1932).

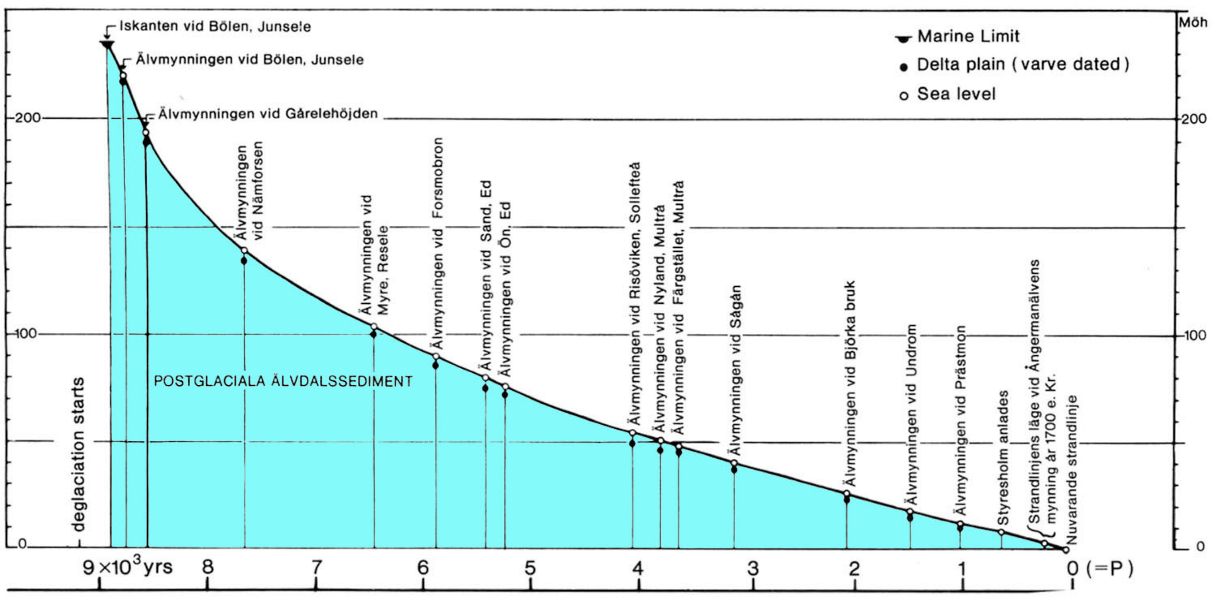

Figure 4. Varve-dated shorelevel displacement curve from Ångermanland by Lidén (1938; as redrawn in Mörner, 1979).

3. A period of hesitation and change of focus

With the introduction of the radiocarbon dating method (Arnold and Libby, 1949) things changed, and there suddenly was an alternative method of obtaining absolute ages. Also, quite

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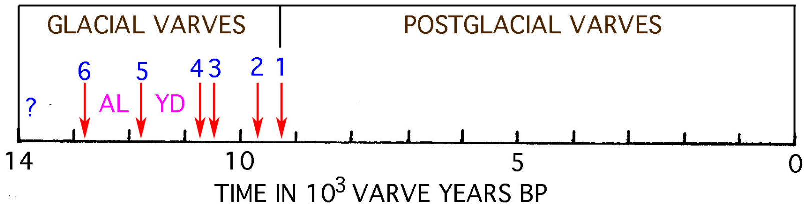

Figure 5. The Swedish Varve Chronology (or Swedish Time Scale) covers about 14,000 varve years back in time: (1) the drainage of the Central Jämtland Ice Lake at varve 9239 BP, (2) a major >8 earthquake at Hudiksvall at varve 9663 BP (and ~9150 C14-years BP), (3) a major >8 earthquake with ingression of salt water into the Baltic basin and the onset of the Yoldia Sea stage (*sensu strictu*) at 10,430 BP, (4) the Drainage of the Baltic Ice Lake, roughly corresponding to the end of the Younger Dryas Stadial, at 10,740 BP, (5) the onset of the Younger Dryas (YD) cold period, (6) the onset of the Alleröd warm period.

bad errors in the varve ages were documented; especially in eastern US and Canada (e.g. Ridge and Larsen, 1990).

Internationally, the application of varve dating, rather switched from the ice recessional records in Sweden (De Geer, 1940), Finland (Sauramo, 1923) and North America (Antevs, 1932) to chronologies of continual lake records.

Annually varved sediments were discovered in a large number of non-glacial lakebeds from other parts of the world. This opened for local absolute dating of lake deposits. Many excellent papers were published (e.g. Anthony, 1977; Kelts & Hsü, 1978; Sturm, 1979; O'Sullivan, 1983; Anderson et al., 1985; Saarnisto, 1985).

4. A period of revision and extension

In Sweden and Finland, we entered into a period of revision. The postglacial varves along River Ånermanälven and the connection to the present were revised by Cato (1987), and an error of +350 varves was established. The varves from Central Sweden to Stockholm were revised by Järnefors (1963) and later Strömberg (1989), who found a minor error of +19 varves. The number of varves between the "drainage of the Baltic Ice Lake" and the immigration of saltwater at Stockholm at De Geer's varve -1073 (De Geer, 1940; Mörner, 1995; Johnson et al., 2013) was set at 292 varves by Sauramo (1923), later at 299 varves by Mörner (1977) and finally 310 varves by Brunnberg (1995), who dated the two events at, respectively, 10,740 and 10,430 BP. Kristiansson (1986) extended the chronology through the Younger Dryas and Alleröd periods, with an additional sequence by Ringberg (1991). So, today, the Swedish Varve Chronology spans some 14,000 varves (Fig. 5) with, as it seems, quite a small margin of error in the varve dating. It must be noted, however, that there still remains a significant discrepancy with respect to calibrated C14-ages, which seems to be as much as in the order of 700 years (Mörner, 2003, p. 179) to 800 years (Wohlfart & Possnert, 2000); the varve ages being too young. The missing varves must be searched for at a time younger than 9663 varves BP, and maybe between 5000 and 2000 BP (Wohlfarth et al., 1997).

Niemelä (1971) revised the Finnish varve chronology. In Estonia and the St. Petersburg area, there are local varve sequences ("floating" varve chronologies) not yet connected to the Finnish and Swedish time scales (Hang & Kohv, 2013).

5. The application of events, spatial distribution and rates

Varve dating is very useful when it concerns the dating of the duration of a geological event. De Geer (1940) was able to show the mode of ice recession and date esker centra and moraine ridges as to single years (Fig. 2). Varve chronology also gives the background for rate calculations. The classical example is the rate of ice retreat and its changes over time (De Geer, 1940). The rate of ice marginal recession over the Stockholm area was in the order of 300 m per year, despite the fact that the ice flow to the front was in the order of 500 m per year, implying a total annual melting of about 700-800 m. This is an enormous rate of ice melting (Fig. 3a). Still, the rate of global sea level rise was in the order of 10 mm/year. This value is of great significance, because all present-day sea level changes must be well below this value (Mörner, 2011).

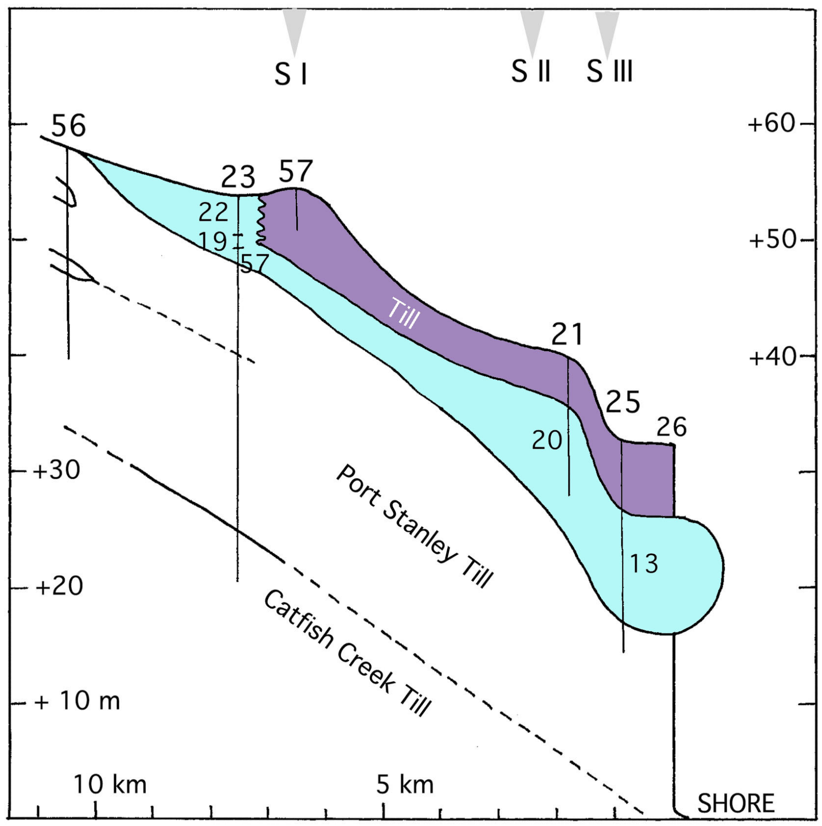

Figure 6. Stratigraphy of the Kettle Creek at the northern shore of Lake Erie including three separate till beds, the last one of which is underlain by varves indicating a readvance of about 8 km and halt of 22 years for the building up the Tillsonburg–Sparta I (SI) Moraine (Mörner, *Ice recession and varve chronology in southern Ontario*, unpublished).

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The deglaciation of the Ontario region in Canada is characterized by a number of end moraines representing halts or minor re-advances. By applying a relative varve chronology, it was possible to date the duration of the building up of the Tillsonburg Moraine at 22 years (Fig. 6). A varve sequence right in front of the Tillsonburg-Sparta I end-moraine includes 98 varves; 57 recessional varves, 19 readvance varves and 22 ice-marginal varves. This indicates a readvance in the order of 8 km and time of ice-marginal halt of only 22 years.

In a few cases it has been possible also to pinpoint the season of an event. This is the case for a major earthquake in Sweden, which was shown to have occurred in the autumn of varve 10,430 BP (Mörner, 2003, 2011, 2013a).

Because different events in Sweden could be tied to one and the same varve, it was possible to document the spatial distribution of those events. This has been especially useful in paleoseismology (Mörner, 2003, 2011, 2013a; Mörner & Sun, 2008). Turbidites were recorded at single varves and their spatial distribution recorded. There is a relation between seismic magnitude and the spatial distribution of liquefaction. Thanks to the varve chronology in Sweden, a paleoseismic event occurring in varve 10,430 BP was shown to have generated liquefaction over an area of 320x100 km, indicating that this event must have had a magnitude of >8 on the Richter scale.

In the glacial varves in the Stockholm region, it was possible to document and date seven separate paleoseismic events within the period 10,490 to 10,388 varves BP (Mörner, 2011); i.e. 7 events in 102 years. This is a very high seismic frequency (or recurrence time). This record could only have been achieved thanks to the firm varve dating.

At Hudiksvall at the coast of central Sweden, the difference in elevation (7,8 m) and difference in time (~25 varves) between the Baltic level at the deglaciation and at a tsunami event in varve 9663 BP was known (Mörner, 2003, p. 183). Consequently the relative land uplift must have been in the order of 31 cm per year (with eustatic calibration corresponding to a rate of absolute uplift in the order of 40 cm/yr). This is a unique value, which provides a very accurate measurement of the rate of uplift right after the free-melting.

Micro-varved postglacial lake sequences occur both in Sweden and Finland. They provide excellent chronological tools for the recording and dating of environmental changes (e.g. Renberg, 1983; Renberg et al., 1984; Ojala & Tiljander, 2003; Ojala et al., 2008; Ojala et al., 2013). This also includes the recording and dating of secular paleomagnetic changes in the Holocene (Ojala & Tiljander, 2003). Maier et al. (2013) were able to assess the rate of sediment compaction; after 3-5 years the varve thickness had decreased by 60%.

Lake Kassjön at Umeå in northern Sweden has lake sediments that are annually varved for the last 6300 years. We applied paleomagnetic studies of these deposits (Mörner and Sylwan, 1989). A major swing in declination was recorded at around 2600 varves BP, which is about where the production of ^{14}C records a major spike. Ten samples were C14-dated over the swing in declination (the same sample as paleomagnetically analysed). Declination swings to the west by 117^{o} in 348 years, which implies implies a rate of 0.36^{o} per year. This change constitutes a "trans-polar VGP shift" (Mörner, 1991). It coincides with the main spike in ^{14}C-production. Therefore, this event is likely to represent an internal perturbation of the Earth's own geomagnetic field and not Solar Wind driven change of the geomagnetic shielding and ^{14}C production (Mörner, 2013b).

The very long varved core sequence from Lake Suigetsu in Japan extends the C14-calibation back to 45,000 BP (Kitagawa & van der Plicht, 2000).

Finally, it may be of historical interest to note that Wilson already in 1943 reported on a varve-sequence of 12,223 varves from the southwestern part of Lake Erie (Wilson, 1943).

6. Pre-Quaternary varves

Varved sediments are, of course, not restricted to the Quaternary period. Glacial varves are recorded for all previous glaciations, too. The Permian varves in Brazil provide fine examples of glacial varves, and have led to the establishment of a special exhibition park known as *Parque do Varvito* where the varves are excellently preserved (Fig. 7). The Late Precambrian (~650 Ma) varves of the Elatina Formation in Australia (Williams, 1985) are important because they provide records of a "~12-laminae cycle" interpreted as the 11-yr solar cycle.

Figure 7. Parque do Varvito exhibiting Permian varves. *Right:* view of the main sequence. *Left:* close-up of proximal varves in the centre including an ice-rafted block.

7. Conclusions

"The Swedish Varve Chronology" was invented and built up by De Geer (1940). With much revision and addition, the chronology now covers a period of about 14,000 years. It is based on the successive correlation of varve segments representing the deposition of varved clay in front of the receding ice margin (on-lapping varves) plus the postglacial varves of deltaic river varves down the River Ångermanälven (off-lapping varves). The sequence older than about

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9500 varved BP has an error of about 700 missing varves with respect to the radiocarbon calibrated chronology.

Varve records have a great potential when it comes the determinations of durations and rates of a large variety of events recorded by the varves. In this case, the chronology needs not to be fixed to the present, but may also be a "floating chronology" just providing a short sequence of precise annual determination. This applies for all varve records from deposits older than the Last Ice Age (e.g. Williams, 1985).

Continual varve sequences from lakes basins offer local chronologies of very high precision (e.g. Kitagawa & van der Plicht, 2000; Ojala & Alenius, 2005), and can be used to date a large number of local environmental changes. Today, this application of varve records seems to be more important (VWG, 2014) than the building up of local chronologies like the famous "Swedish Time Scale" or "Swedish Varve Chronology".

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